96

VOLUME 81 SEPARATE No. 596

PROCEEDINGS

AMERICAN SOCIETY OF CIVIL ENGINEERS

JANUARY, 1955

DETERMINING THE REQUIRED THICKNESS OF CONCRETE PAVEMENTS FOR HIGHWAYS

by Joseph Herbert Moore, J.M. ASCE

HIGHWAY DIVISION

{Discussion open until May 1, 1955}

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE $0.50 PER COPY

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This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

DETERMINING THE REQUIRED THICKNESS OF CONCRETE PAVEMENTS FOR HIGHWAYS

Joseph Herbert Moore,[1] J. M. ASCE

SYNOPSIS

The most widely used method of determining the thickness of Portland cement concrete pavements for highways is based on wheel loads being placed at the corners of the slabs. This paper presents data which indicates that the longitudinal edge loading position is really the critical loading position when the restrained warping stresses and lateral distribution of vehicles across the traffic lanes are rightly considered.

A table of "load percent factors" is given to simplify the recommended design method and make it practical and easy to apply. For numerous traffic patterns the new design method indicates that pavements of 8 or 9 inch thickness give longest life, and pavement life can be remarkably increased by providing very strong subgrade support.

INTRODUCTION

The determination of the proper thickness for a concrete pavement slab for a highway has apparently remained so complex that highway engineers often base their choice of thickness entirely upon their individual experiences with former cases. The PCA[2] method of determining the thickness has been used by several states, but the semi-empirical equation by Pickett[3] which is the basis for the PCA design method is based upon a wheel load placed only at the corner of the pavement slab. This type of loading should produce cracks diagonally across the corner; yet in a recent study[4] of this problem in Pennsylvania the corner crack was found to be a rare exception whereas the large majority of cracks were transverse cracks almost at right angles to the longitudinal axis of the pavement slab.

For several years the Pennsylvania Department of Highways has collected detailed traffic data at a number of loadometer stations throughout the state, and has kept rather complete records of pavement performance within designated portions of the highways at these loadometer stations. Many of these strips had Portland cement concrete pavements and thereby presented an excellent yardstick to measure any empirical or theoretical design method. In

1. Asst. Prof. of Civ. Eng., The Pennsylvania State Univ., State College, Pa.

2. Concrete Pavement Design, Portland Cement Association, Chicago, Illinois, 1951.

3. Pickett, Gerald, "A Study of Stresses in the Corner Region of Concrete Pavement Slabs Under Large Corner Loads," Concrete Pavement Design, Portland Cement Association, Chicago, Ill.; 1951, pp. 77-86.

4. Highway use and highway cost study conducted by Haller, Raymond, and Brown, Inc., for the Joint State Government Commission of Pennsylvania in 1952.

addition to these strips along which the traffic figures were well known, a large number of one-mile strips of concrete pavements were chosen at random throughout the state and estimates were made of the present traffic on each strip and the life of the existing pavement; then the design method developed in the study was applied to these pavements also and a good correlation was noted between the computed and the field estimate of the pavement life.

The design procedure developed was measured against highways in Pennsylvania and is therefore for pavements with a reasonable amount of distributed steel, tie bars, and dowels. The use of distributed steel in Pennsylvania highways has grown from 42 pound mats to use of 72 pound mats at the present time. The size and spacing of dowels has varied but the spacing of tie bars of 9/16 inch diameter at five foot intervals across longitudinal joints has been about uniform practice.

Any assumptions or major premises used in the design method will be discussed under the particular factor involved.

Major Factors Affecting the Required Pavement Thickness

1. Subgrade and Drainage: The year-round bearing capacity of the subgrade is of primary importance and is probably the largest factor in determining how long a pavement will support heavy loads before cracking. Permanent settlement or deflection of the subgrade beneath a slab will leave the slab unsupported, and, if the soil is susceptible to pumping, a combination of heavy loads and free water beneath the slab will lead to the forming of transverse cracks about four or five feet from the end of the slab.

A major premise in this paper is that the subgrade must be constructed to prevent pumping. This, in itself, presents a major problem, in the solution of which the soils engineer, field inspector, and contractor all play important roles.

The dependable bearing capacity of the subgrade must be known in order to determine the thickness of the pavement slab. Plate bearing tests using 30-inch diameter plates are suggested as the most satisfactory means of determining bearing capacity.

2. Traffic: To determine the thickness of a pavement slab for a particular road the engineer must obtain the following traffic data:

a. Total traffic per lane
b. Percent of trucks or commercial traffic
c. Average number of axles per truck
d. Number of axles in each thousand-pound weight category

When a highway is to be designed for future traffic it is obvious that someone must estimate the above items. Too often no estimate is made now of the number of axles per truck and no measurements are made on comparable roads to determine the weight category of the axles. Therefore no real consideration is given to the number of applications of the various axle loads.

3. Lateral Distribution of Traffic: It is apparent to the layman, as well as the engineer, that vehicles do not track each other on a highway. However, a comprehensive search of available literature failed to reveal a design method for concrete pavements which considered this lateral distribution of wheel loads.

Taragin[5] reported some values for the lateral distribution of traffic and Table 1 presents an interpretation of his data. As would be expected, Table 1 reveals that narrow pavement lanes lead to more numerous commercial or truck loads near the transverse edge than do wider pavement lanes.

Placement of right wheels to left of the right edge	Lane Widths			
	9-foot	10-foot	11-foot	12-foot
	%	%	%	%
1/2 - foot	15.7	5.8	1.6	0.7
1 - foot	17.7	11.7	3.8	1.8
1 1/2 - feet	23.6	17.5	8.4	3.7
2 - feet	18.6	18.7	16.6	6.6
2 1/2- feet	12.5	18.6	22.9	10.6
3 - feet	6.7	14.2	17.9	15.4

Table 1. Lateral Distribution of Commercial Traffic

4. Points of Largest Unit Tensile Stress: When concrete pavements crack they do so because of excessive tensile stresses. The major sources of these stresses are: a) Direct tensile stresses produced by contraction of the slab; b) Flexural tensile stresses caused by wheel loads on the slab; c) Flexural tensile stresses caused by restrained warping of the slab.

Longitudinal steel is customarily introduced into all pavements in Pennsylvania and the wide spread practice has been to put in enough steel to resist computed contraction stresses. Average values for these stresses are not difficult to compute for any length of slab if reliable values are available for the thermal coefficient of the concrete and the coefficient of friction between slab and subgrade. The proper coefficient of friction to use is still an open question, and this paper will not touch this problem; a value of 1.5 has often been used and is apparently very conservative. Since sufficient longitudinal steel is provided in Pennsylvania to resist the tensile stresses introduced by contraction of the slab in cold weather, this item was eliminated from further consideration in the study.

For a concrete pavement slab the wheel load may be at any of four general positions: at the interior, along a longitudinal edge, at a transverse edge, or at the corner of the slab. If the only stresses in the slab were those from the wheel loads, the corner loading position would in all probability introduce the largest unit stress in the concrete. But the Arlington Road Tests[6] and Road Test One-Md[7] (see Figure 1) indicated that restrained

5. Taragin, A., "Effect of Roadway Width on Vehicle Operation," Public Roads, Vol. 24, No. 6, 1945.

6. Teller, L. W., and Sutherland, E. C., "The Structural Design of Concrete Pavements, Part II-Observed Effects of Variations in Temperature and Moisture on the Size, Shape, and Stress Resistance of Concrete Pavement Slabs," Public Roads, Nov. 1935.

Footnote seven appears on following page.

warping stresses along the longitudinal edge of a slab may be very large, whereas near the corner or along the transverse edge they are usually insignificant. These restrained warping stresses are caused by the resistance offered by the weight of the slab and the friction between pavement and subgrade to the free warping of the pavement caused by temperature and moisture differentials at the top and bottom of the slab. The designer's problem is therefore to investigate and determine whether a particular pavement will develop transverse cracks due to the combination of load and restrained warping stresses at the interior or along the longitudinal edge of the slab before this same slab would fail diagonally across the corner.

A comprehensive search of the literature revealed that the analysis by Westergaard[8] and the extensive Arlington Road Tests (reported by Teller and Sutherland)[9] provide the most exact coverage the subject has experienced. The Arlington tests were planned with the purpose of checking the validity of Westergaard's theoretical equations, and in general remarkable agreement was obtained between computed and measured load and restrained warping stresses at various points in the slab. The chief exception to this agreement was the maximum load stress from the interior loading position.

For this position of loading Westergaard then noted that the reactions of the subgrade might be expected to be more closely concentrated around the load than the deflections would be in a body continuous in two directions, and he modified[10] his earlier equation for this load stress to include two additional unknowns. Unfortunately these unknowns, "L" and "Z," can only be evaluated by field tests on pavements at each particular site. However both Westergaard and Bradbury [11] suggested limits for "L" and "Z;" and these values were used in preliminary calculations for this paper in order to ascertain whether or not the unit load and restrained warping stresses at the under side of the slab for this wheel loading would be as detrimental as those for the longitudinal edge loading position. Since "L" and "Z" could vary widely from one site to another, the calculations were of little help but the longitudinal loading position appeared to present larger total unit stresses so the interior loading position was not considered further.

The transverse edge loading stresses and restrained warping stresses did not prove to be of appreciable magnitude in this study, so this general loading position was also eliminated--confining the study to the largest unit tensile stresses produced at the critical sections for the corner and longitudinal edge loading. The longitudinal edge considered was the free edge.

Westergaard's equation for the maximum unit stress in a longitudinal direction beneath a load applied during the day at the longitudinal edge of the

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7. "Final Report on Road Test One-Md," Special Report 4, Highway Research Board, Washington, D. C., 1952.

8. Westergaard, H. M., "Stresses in Concrete Pavements Computed by Theoretical Analysis," Public Roads, Vol. 7, No. 2; April 1926, pp. 25-35.

9. Teller, L. W. and Sutherland, E. C., "The Structural Design of Concrete Pavements" (Five Parts), Public Roads; Oct, Nov, Dec 1935; Sept, Oct, April, and May 1936.

10. Westergaard, H. M., "Analytical Tools for Judging Results of Structural Tests of Concrete Pavements," Public Roads, Dec. 1933.

11. Bradbury, R. D., "Reinforced Concrete Pavements," The Wire Reinforcement Institute, Washington, D. C., 1938, p. 31.

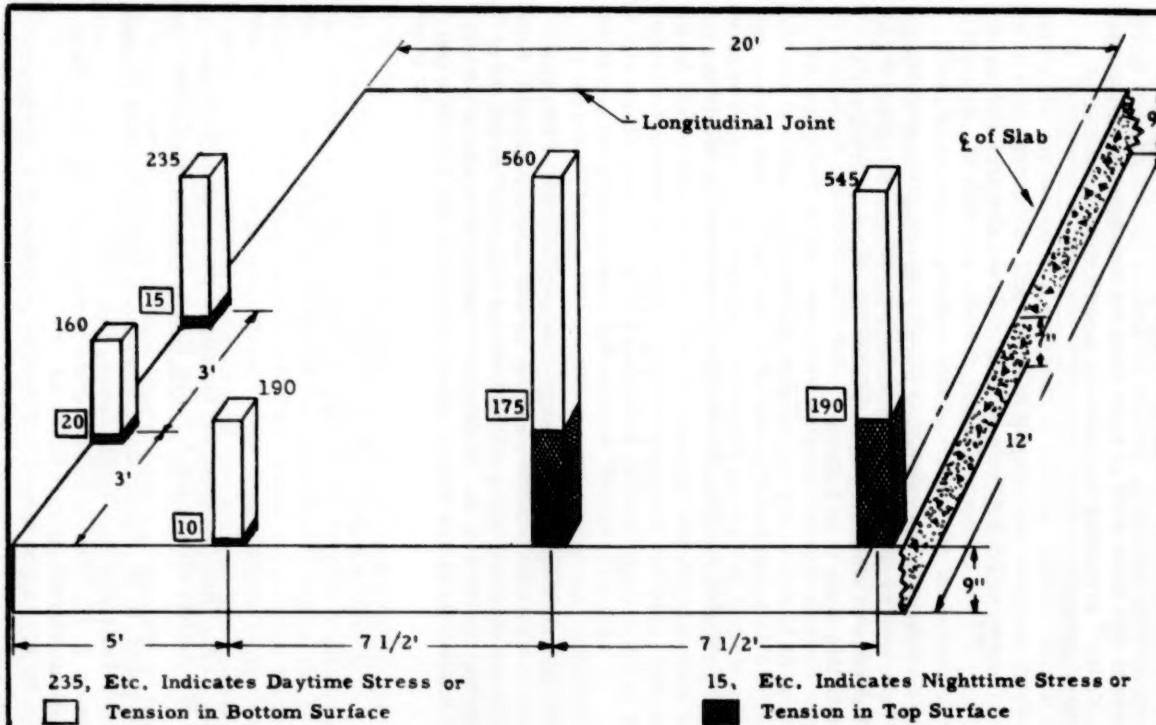

Figure 1. - Measured Stresses Caused by Restrained Temperature Warping Along a Traverse Joint and Longitudinal Free Edge of a 12- by 40-Foot Slab (Road Test One-Md).

slab reduces to the following for a Poisson's ratio of 0.15:

$$\sigma_{ex} = 0.57185 \frac{P}{d^2}\left[4 \log_{10} \frac{l}{b} + 0.3593\right]$$

For load stress at this same point at night when the slab tries to curl upward at the edges, Kelley[12] presented the following modification of another of Westergaard's equations:

$$\sigma_{ex} = 0.57185 \frac{P}{d^2}\left[4 \log_{10} \frac{l}{b} + \log_{10} b\right]$$

Westergaard's equations for restrained warping stresses[13] near the longitudinal edge were lengthy and involved hyperbolic functions. Bradbury[14] and Kelley[15] each presented simplified equations for this stress. Bradbury's equation used in this study is as follows:

$$S_{ex} = \frac{C E e \Delta t}{2}$$

For the corner loading position, Westergaard suggested the following equation:

$$\sigma_c = \frac{3P}{d^2}\left[1 - \left(\frac{a_1}{l}\right)^{0.6}\right]$$

Kelley, Bradbury, and Spangler[16] have suggested modifications of this theoretical equation for various reasons including loss of subgrade support. Pickett compared these equations along with others and suggested the following equation which has the form of the Westergaard theoretical equation but also more closely follows the larger stress values obtained in the Arlington tests:

$$\sigma_c = \frac{4.2P}{d^2}\left[1 - \frac{\sqrt{a_1/l}}{1.1 + 0.185\, a_1/l}\right]$$

12. Kelley, E. F., "Application of the Results of Research to the Structural Design of Concrete Pavements," Public Roads, Vol. 20, No. 5, July 1939, p. 90.

13. Westergaard, H. M., "Analysis of Stresses in Concrete Roads Caused by Variations of Temperature," Public Roads, May 1927.

14. Bradbury, R. D., "Reinforced Concrete Pavements," The Wire Reinforcement Institute, Washington, D. C., p. 39.

15. Kelley, E. F., "Application of the Results of Research to the Structural Design of Concrete Pavements," Public Roads, Vol. 20, No. 5, July 1939, p. 96.

16. Spangler, M. G., "Stresses in the Corner Region of Concrete Pavements," Iowa Engr. Exper. Station, Bulletin 157, Ames, Iowa, Sept 1942.

Pickett's equation for the corner loading position has been widely accepted and was used in this study.

The equations for the longitudinal edge loading stress chosen by the writer were those that showed the closest agreement with values measured in the Arlington tests.

5. Frequency of Load and Restrained Warping Stresses being Additive: During the day the top of a pavement is warmer than the bottom so the edges try to curl downward. The weight of the slab and subgrade friction tend to prevent this action and thereby tensile stresses are produced in the bottom of the slab. At night the effect is just the opposite.

Wheel loads always produce tensile stresses in the bottom of the slab immediately under the load for the longitudinal edge loading position. Therefore it is only in the daytime that load and warping stresses at such a point could be additive. In this study such stresses were considered to be additive for only about six hours each day.

The magnitude of the restrained warping stresses depends upon temperature and moisture differentials between top and bottom of the slab. The former has the major effect and in the spring and summer this differential may be approximated as 3 degrees Fahrenheit per inch of slab thickness; in the fall and winter it may be reduced to 2/3 this amount. On this basis 1/8 of the annual traffic may be assumed to be passing over the slab when the largest restrained warping stresses are additive to load stresses, and another 1/8 of this annual traffic may be assumed to be passing when 2/3 of the maximum restrained warping stresses are additive to load stresses.

To the casual reader this condition may suggest the erroneous conclusion that this reduced amount of effective traffic would lead to earlier failure due to the corner loading. Figure 2 shows the magnitude of the stresses that can exist for the corner or the longitudinal edge loading positions, but it should be noted that only those stresses above 50% of the flexural modulus of rupture of the concrete (350 psi in Figure 2) will have any appreciable effect in producing cracking.

6. Influence of Lateral Position of Load on Load Stress: Both the Arlington Road Tests and the Road Test One-Md reports contain data regarding this subject. The latter report reveals that the stress in a longitudinal direction at a point six inches from the free longitudinal edge of the pavement would be reduced from 100% to 40% if the wheel were moved transversely from this point to a position thirty inches from the free edge. The reduction in stress curve is practically a straight line between these two positions. For the corner loading the reduction in stress at the critical section is from 100% to 60% for a similar lateral shift of the load.

These reductions are of much interest since a complete analysis of load stresses at a point must include the effect at that point of loads one, two, or possibly three feet from the point in a lateral direction.

7. Length of Pavement Slab: From the viewpoint of determining the thickness of a slab, the length of the slab is reflected only in the calculations of the restrained warping stress. Bradbury's curve[17] for the coefficient "C"

17. Bradbury, R. D., "Reinforced Concrete Pavements," The Wire Reinforcement Institute, Washington, D. C., 1938, p. 40.

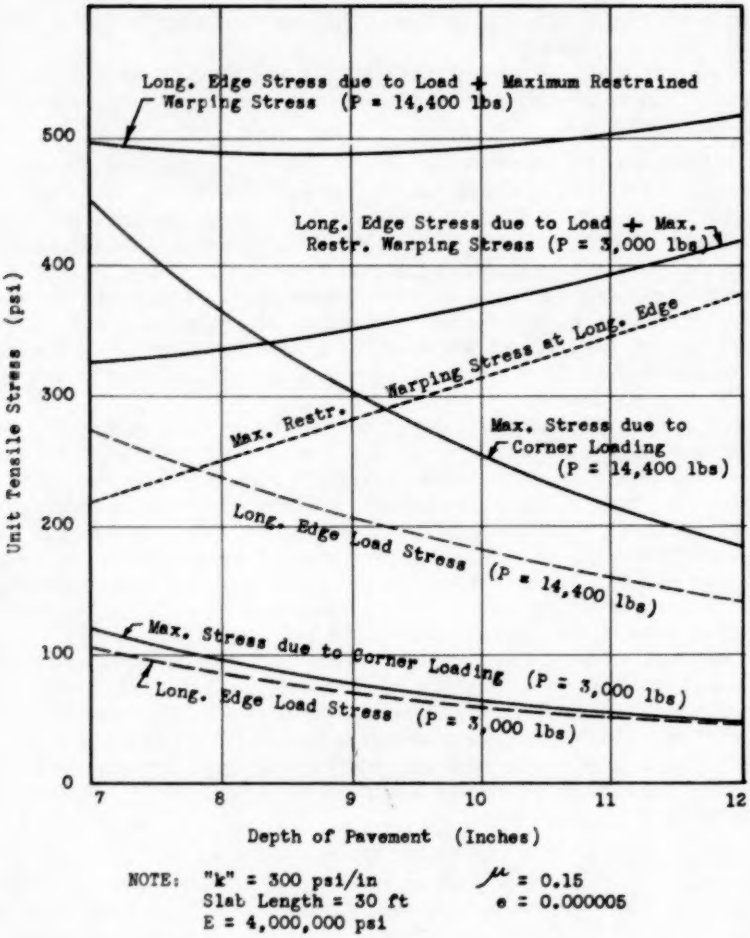

Figure 2. Unit Tensile Stress vs Slab Thickness for the Longitudinal Edge and Corner Loading

clearly indicates that beyond a length of 15 feet there is no further appreciable increase in restrained warping stress with increase in slab length. This also means that slab lengths of less than 15 feet must be used if appreciable restrained warping stresses are to be avoided. In Pennsylvania a slab length of 61 1/2 feet is now being used and since highway slab lengths of less than 15 feet do not appear practical or economical, the design values suggested in this study are based on slab lengths greater than 30 feet.

8. Properties of the Concrete: The flexural modulus of elasticity, Poisson's ratio, and the coefficient of thermal expansion or contraction of concrete directly affect the stresses in the slabs. While these properties undoubtedly will vary to some degree in any length of pavement, the following values were selected as representative and used in this study: $E = 4 \times 10^6$ psi; $\mu = 0.15$; and "e" = 0.000005.

The resistance to failure from numerous applications of unit stresses less than the yield point unit stress is also of interest in such a study as this. While fatigue data for concrete beams in bending is available, there appears to be no such data on large slabs subjected to localized bending stresses. In this study the fatigue curve by Bradbury[18] was used to determine the relative detrimental effects of different unit stresses.

The Design Method

Having limited the possibilities of failure to cracking across the corner due chiefly to loads on or near the corner, or to transverse cracking due to tensile stresses in the bottom of the slab at points near the longitudinal free edge of the pavement; these two loading positions were then examined in detail and curves for load stress and restrained warping stress were constructed.

The commercial traffic on a given highway lane was then considered distributed laterally as indicated by Table 1 in order that the number of wheel loads of each magnitude travelling one or two feet from the point under study would be available. A wheel load 1 1/2 feet from the edge was then known to be only 70% effective in producing longitudinal stress at a point one-half foot from the edge as shown in Road Test One-Md. Such load stresses due to wheels within two or three feet of a point could then be added algebraically to restrained warping stresses at this point. Of course the very worst combinations of load and restrained warping stress for the longitudinal edge loading will only occur under about 1/8 of the yearly traffic, but another 1/8 of the yearly traffic must be used when studying the combined effect of load and the smaller restrained warping stresses due to the temperature differential of 2° F./inch of slab depth which may be expected in the fall and winter. The actual effective repetitions per year of various wheel loads and the combined stress at a point 1/2 foot from the longitudinal edge for a sample case is shown in Table 2.

To add the effects of tensile stresses of various amounts a common denominator was needed. Bradbury's fatigue curve for concrete in bending was used to determine the number of repetitions of each stress required to cause failure; from which by proportion the actual repetitions of a single stress could be converted to equivalent repetitions of any other stress. In this study all wheel load effects were converted to an equivalent number of 5,000 pound wheel loads applied 1/2 foot from the edge when the maximum restrained warping stress is effective.

For the longitudinal edge loading the equivalent 5,000 pound wheel loads produced by the actual number of wheel loads of a particular weight travelling on a pavement slab was expressed as a "load percent factor" in Table 3. The column "Revised Percent Factors" for the 12-foot lane width is given to show that the calculated "Percent Factors" practically lead to a smooth plot. Table 4 presents similar percent factors for 12-foot lanes for various values of pavement thickness and subgrade bearing capacity.

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18. Bradbury, R. D., "Reinforced Concrete Pavements," The Wire Reinforcement Institute, Washington, D. C., 1938, p. 55.

Slab Depth = 8 inches "k" = 200 psi/in						Slab Length = 30 feet Slab Width = 12 feet	
Wheel Load (lbs)	Wheel Position*	Δt	Long. Edge Stress (Load + Warping)	Percent of Modulus of Rupture	Repetitions to cause Cracking	Actual Repetitions per year	Equivalent 5,000 lb Load Repetitions per year**
3000	a		below 350	-	Infinite	-	0
4000	a		363	51.8	550,000	127	39
5000	a		384	54.8	170,000	61	61
	b		357	51.0	850,000	156	31
6000	a		402	57.4	65,000	78	204
	b		372	53.1	340,000	200	100
7000	a		418	59.8	30,000	78	442
	b		384	54.8	170,000	199	199
	c		351	50.1	Infinite	-	0
8000	a	3°/ inch of slab depth	433	61.9	17,000	74	740
	b		396	56.6	90,000	191	361
	c		360	51.4	700,000	393	95
9000	a		448	64.1	8,000	74	1575
	b		408	58.3	48,000	190	673
	c		369	52.7	400,000	390	166
10000	a		463	66.2	3,900	36	1570
	b		421	60.1	28,000	92	553
	c		378	54.0	234,000	189	137
11000	a		473	67.6	2,600	9.1	595
	b		428	61.2	20,000	23.4	199
	c		384	54.8	170,000	48.2	48.2
12000	a		487	69.5	1,500	1.4	159
	b		440	62.8	12,000	3.7	52.4
	c		392	56.0	110,000	7.6	11.7
13000	a		496	70.9	1,040	0.6	102
	b		447	63.9	8,500	1.5	30
	c		398	56.9	80,000	3.1	6.6
15000	a		521	74.4	320	0.3	154
	b		468	66.9	3,150	0.7	37.8
	c		413	59.1	35,000	1.5	7.3
	d		358	51.2	750,000	2.7	0.6
9000	a	2°/ inch of slab depth	365	52.1	500,000	74	25.2
10000	a		380	54.3	210,000	36	29.2
11000	a		390	55.7	120,000	9.1	12.9
12000	a		404	57.7	60,000	1.4	4.0
13000	a		413	59.0	37,000	0.6	2.8
	b		365	52.0	450,000	1.5	0.6
15000	a		438	62.6	13,000	0.3	3.9
	b		383	54.7	180,000	0.7	0.6

* Wheel positions are as follows:
- a. Center of wheel 6 inches from longitudinal edge
- b. Center of wheel 12 inches from longitudinal edge
- c. Center of wheel 18 inches from longitudinal edge
- d. Center of wheel 24 inches from longitudinal edge

** Repetitions of 5,000 lb wheel loads placed at position "a" on slab

Table 2. Computation of Equivalent 5,000 Pound Load Repetitions

WHEEL LOAD	ACTUAL REPETITIONS PER YEAR PER LANE	12 FOOT LANES			11 FOOT LANES		10 FOOT LANES		9 FOOT LANES	
		EQUIVALENT 5,000 LB LOADS	PERCENT FACTORS	REVISED PERCENT FACTORS	EQUIVALENT 5,000 LB LOADS	PERCENT FACTORS	EQUIVALENT 5,000 LB LOADS	PERCENT FACTORS	EQUIVALENT 5,000 LB LOADS	PERCENT FACTORS
4,000	145,000	39	0.03	0.05	89	0.06	323	0.22	875	0.60
5,000	69,200	92	0.13	0.13	204	0.30	706	1.02	1,675	2.42
6,000	89,000	304	0.34	0.39	677	0.76	2,340	2.6	5,553	6.2
7,000	88,600	641	0.73	0.77	1,430	1.6	4,950	5.6	11,860	13.4
8,000	85,000	1,196	1.4	1.5	2,667	3.1	8,929	10.5	20,756	24.4
9,000	84,200	2,439	2.9	2.9	5,455	6.5	18,464	21.9	43,545	51.7
10,000	40,750	2,289	5.6	5.2	5,138	12.6	17,490	42.9	42,169	105.0
11,000	10,400	855	8.2	8.2	1,919	18.4	6,555	63.0	15,907	153.0
12,000	1,642	227	13.8	13.6	510	31.0	1,748	107.0	4,250	258.0
13,000	660	142	21.5	23.6	319	48.4	1,099	165.0	2,696	407.0
15,000	330	204	61.8	63.3	460	139.0	1,599	484.0	3,984	1,210.0
Totals		8,428			18,868		64,203		153,270	
Crack Resistance Factor		$\frac{170,000}{8,428}$ = 20.4 years			$\frac{170,000}{18,868}$ = 9.1		$\frac{170,000}{64,203}$ = 2.7		$\frac{170,000}{153,270}$ = 1.1	
Ratio of Crack Resistance Factors		$\frac{20.4}{20.4}$ = 1.0			$\frac{20.4}{9.1}$ = 2.24		$\frac{20.4}{2.7}$ = 7.55		$\frac{20.4}{1.1}$ = 18.5	

Note: Pavement Depth = 8 inches
"k" = 200 psi/in

Table 3. Calculation of Load Percent Factors

WHEEL LOAD (lbs)	"k" under 100				"k" of 100-175				"k" of 175-225				"k" of 225-275				"k" over 275			
	d = 7	8	9	10	7	8	9	10	7	8	9	10	7	8	9	10	7	8	9	10
3000	0	0.01	0.01	0.03	0.02	0.01	0.01	0.05	0	0	0.01	0.04	0.02	0.01	0.01	0.05	0	0	0	0.04
4000	0.06	0.07	0.09	0.11	0.04	0.04	0.06	0.09	0.03	0.05	0.05	0.09	0.04	0.03	0.05	0.09	0.04	0.04	0.06	0.10
5000	0.12	0.13	0.18	0.22	0.11	0.12	0.17	0.27	0.09	0.13	0.16	0.24	0.07	0.09	0.15	0.25	0.09	0.09	0.15	0.26
6000	0.50	0.39	0.43	0.42	0.31	0.33	0.35	0.49	0.39	0.39	0.40	0.51	0.27	0.29	0.37	0.48	0.26	0.24	0.36	0.52
7000	1.30	0.98	0.90	0.84	0.86	0.77	0.70	0.85	0.95	0.77	0.79	0.97	0.72	0.66	0.73	0.83	0.62	0.58	0.74	0.78
8000	3.2	2.1	2.0	1.5	2.4	1.8	1.4	1.4	2.4	1.5	1.1	1.3	1.8	1.3	1.4	1.3	1.3	1.1	1.3	1.2
9000	8.7	5.5	3.9	2.9	5.1	3.6	2.6	2.3	5.1	2.9	2.3	1.9	3.8	2.6	2.3	2.0	2.5	2.1	2.3	1.9
10000	22.4	12.3	7.4	5.0	10.2	6.9	4.6	3.9	9.2	5.2	3.8	3.0	6.8	4.5	3.8	3.0	4.5	3.7	3.8	2.9
11000	40.5	25.9	13.2	7.8	18.4	11.3	7.5	5.8	15.2	8.2	5.9	4.6	11.4	7.3	5.8	4.3	7.9	6.4	5.7	3.9
12000	50.4	34.7	23.4	13.0	31.8	19.2	11.8	8.1	25.6	13.6	9.3	5.8	19.1	11.7	9.0	5.8	12.8	10.0	8.3	5.4
13000	78.6	47.7	38.6	20.8	54.1	31.1	19.2	12.9	48.6	23.6	17.2	9.7	34.3	19.4	14.7	9.4	19.6	14.8	11.9	7.7
15000	199	111	80.0	42.1	148	71.5	41.2	28.1	138	63.3	39.8	23.1	91.9	48.1	32.9	18.4	45.5	32.9	25.8	13.7
17500	468	240	149	71.7	220	142	88.0	48.0	220	117	61.6	31.6	140	88.0	52.0	26.0	77.5	60.7	41.5	21.2
20000	2880	402	281	136	370	268	162	75.0	322	252	101	54.5	230	160	87.0	44.0	140	105	68.1	33.0

"k" = Subgrade Modulus in Psi/inch as determined by Plate Bearing Tests.
d = Thickness of Concrete Pavement in Inches.

Table 4. Percent Factors to Convert Various Wheel Load Effects to Equivalent 5,000 Pound Wheel Loads (For 12-foot Lanes)

The "Crack Resistance Factor" in Table 3 was obtained by dividing the number of 5,000 pound loads one-half foot from the edge that are required to cause failure, by the total equivalent 5,000 pound wheel loads produced by the particular traffic pattern in this problem. The numerator in this calculation appears as the ordinate in the "Concrete Pavement Design Curves" shown in Figure 3. Figure 3 was constructed using computed stress values and Bradbury's fatigue curve.

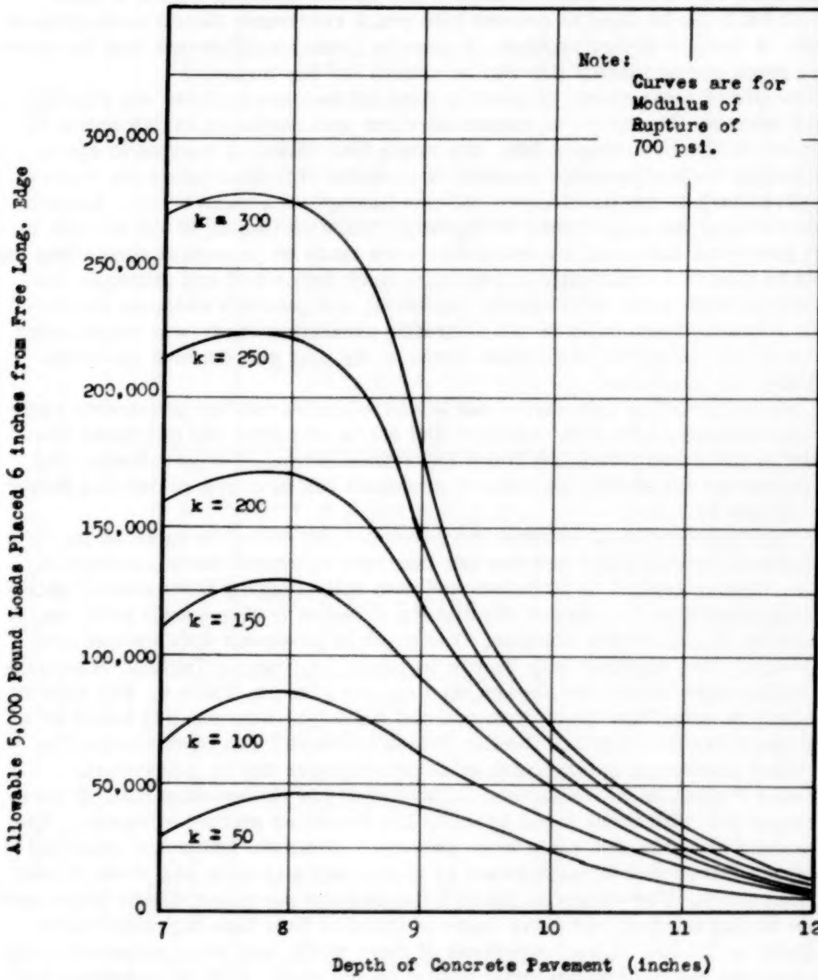

Figure 3. Concrete Pavement Design Curves

The ratio of the crack resistance factors illustrated in Table 3 proves to be most interesting. Computations similar to those of Table 3 were made for 12, 11, 10, and 9 foot width of lanes for all of the combinations of depth and subgrade support indicated in Table 4. The ratios of crack resistance factors of 11, 10, and 9 foot slab widths to those of 12 foot slab width were always very close to 2.25; 8.1; and 18.0 respectively. Therefore there was no need to present percent factors in Table 4 for other than 12 foot slab widths.

The "Percent Factors" in Table 4 can be used to convert any traffic pattern on a pavement lane to equivalent 5,000 pound loads applied 1/2 foot from the longitudinal free edge of the slab. The crack resistance factor can then be calculated, and if the pavement lane is not 12 feet wide the ratios of 2.25; 8.1; or 18.0 can be used to convert this crack resistance factor to its proper value. A sample design problem is given in Table 5 to illustrate how the pavement depth giving longest life can be chosen for any highway.

The life of a pavement, of course, does not become zero the day the first crack occurs. Therefore an empirical value was needed to relate crack resistance factor to pavement life. To obtain this value, as well as to check this design method in every possible way, detailed inspections were made of the pavements at the loadometer stations throughout Pennsylvania. Superintendents from the Department of Highways made estimates of the life left in each pavement and separate estimates were made by personnel conducting the study to assure a uniformity in reporting such data. Soil and drainage conditions at these sites were closely observed, and possible seasonal fluctuations of traffic were considered. A traffic prediction curve was constructed, based on the collection of gasoline taxes in the past and the best estimates available for the future.

Conclusions from this part of the study indicated that for pavements resting on subgrades with a "k" value of 250 psi/in or better the pavement life would be about two times the crack resistance factor. For pavements resting on poorer subgrades the ratio of pavement life to crack resistance factor was chosen as 1.3.

With these empirical factors, the pavement life based on applications of 10,000 commercial axles per day per lane was computed for pavements of depths ranging from 7 to 10 inches and with soils ranging from good to poor bearing capacities for each of the sixteen different traffic weight patterns measured at loadometer stations. The depth of pavement which would give the longest life, together with its life in years, is given in Table 7. The traffic weight patterns for the sixteen stations are given in Table 6. For clarity it should be noted that 10,000 commercial axles per lane per day would be a very heavy traffic load; and the life values in Table 7 can be converted for any other number of commercial axles per lane per day by proportion.

Table 8 contains a comparison of pavement life values estimated by careful inspection with those found by using the foregoing method of design. The pavements listed in this table were chosen to illustrate additional practical problems introduced by such items as multi-lane highways and slabs of non-uniform depth. For values in Table 8 the average pavement depths were used in the design method; and outer lanes of three or four lane highways were analyzed as 12-foot lanes regardless of their width, and were assumed to take one-half the two-way commercial traffic on the road. Such assumptions for the traffic on multi-lane highways may be questioned but these assumptions were chosen after considering the manner in which trucks tend to stay away

Given: Modulus of subgrade support is 200 psi/in
Average Daily Traffic is 7700. Percent Commercial is 28%
Average axles per commercial vehicle = 2.60 (Tandem axle = 2 axles)
Commercial traffic pattern as in column (b)
Percent Factors in columns (d),(f),(h), and (j) from Table 4

Questions:
A. What is the best thickness of pavement to use?
B. If two 12-foot lanes are constructed how long will the pavement last?

Wheel Load (lbs)	Commercial Traffic Pattern (%)	Distribution per 100,000 Commercial Axles	Thickness--7 inches		Thickness--8 inches		Thickness--9 inches		Thickness--10 inches	
			5,000 lb Percent Factor	Equiv. 5,000 lb Loads	5,000 lb Percent Factor	Equiv. 5,000 lb Loads	5,000 lb Percent Factor	Equiv. 5,000 lb Loads	5,000 lb Percent Factor	Equiv. 5,000 lb Loads
3000	30.3	30,300 axles	0	-	0	-	0.01	3	0.04	12
4000	16.4	16,400 axles	0.03	5	0.05	8	0.05	8	0.09	15
5000	7.9	7,900 axles	0.09	7	0.13	10	0.16	13	0.24	19
6000	10.1	10,100 axles	0.39	39	0.39	39	0.40	40	0.51	52
7000	10.0	10,000 axles	0.95	95	0.77	77	0.79	79	0.97	97
8000	9.6	9,600 axles	2.4	230	1.5	144	1.1	106	1.3	125
9000	9.6	9,600 axles	5.1	489	2.9	278	2.3	222	1.9	181
10000	4.6	4,600 axles	9.2	423	5.2	240	3.8	175	3.0	138
11000	1.2	1,200 axles	15.2	183	8.2	98	5.9	71	4.6	55
12000	0.2	200 axles	25.6	51	13.6	27	9.3	19	5.8	12
13000	0.07	70 axles	48.6	34	23.6	17	17.2	12	9.7	7
15000	0.03	30 axles	138	41	63.3	19	39.8	12	23.1	7
Totals	100.00%	100,000 axles	--	1597	--	957	--	760	--	720
(a)	(b)	(c)	(d)	(e)=(c)x(d)	(f)	(g)=(c)x(f)	(h)	(i)=(c)x(h)	(j)	(k)=(c)x(j)

Answers:

A.
For 7-inch depth: 158,000/1597 = 99
For 8-inch depth: 170,000/957 = 177 ← Use 8-inch depth for longest life.
For 9-inch depth: 120,000/760 = 158
For 10-inch depth: 59,000/720 = 82

Note: Numerators in above calculations obtained from Figure 3, "Concrete Pavement Design Curves". Denominators (i.e. 1597, 957, 760, and 720) obtained from Columns (e),(g),(i), and (k) respectively.

B.
Present Traffic Rate $= \frac{7700(365)}{2}(0.28)(2.60) = 1{,}022{,}000$ Comm. axles per lane per year.

Transverse Crack Expectancy $= 100{,}000\left(\frac{170{,}000}{957}\right) = 17{,}750{,}000$ Axles.

Therefore;
Crack Expectancy $= \frac{17{,}750{,}000}{1{,}022{,}000} = 17.3$ years

Pavement Life = 1.3(17.3) = 22.5 years

Table 5. Sample Design Problem

WHEEL LOAD (lbs)	PERCENT DISTRIBUTION OF COMMERCIAL WHEEL LOADS														
	HEAVY					MEDIUM							LIGHT		
	Sta. L-53	Sta. L-182	Sta. L-123	Sta. L-502	Sta. L-136	Sta. L-169	Sta. L-88	Sta. L-32	Sta. L-132	Sta. L-110	Sta. L-104	Sta. L-159	Sta. L-12	Sta. L-192	Sta. L-59
under 3000	36.4%	21.8%	28.2%	20.2%	21.1%	44.6%	43.3%	51.7%	32.8%	30.3%	41.0%	50.0%	49.2%	47.5%	55.7%
4000	12.8	10.4	15.2	6.5	9.4	10.3	14.5	12.3	11.8	16.4	17.2	12.1	12.6	14.7	9.8
5000	7.3	11.2	8.6	10.5	9.5	9.1	10.8	6.4	9.8	7.9	8.0	5.0	8.3	9.1	9.5
6000	9.9	12.8	7.7	13.7	13.8	9.1	8.7	9.3	8.3	10.1	8.2	6.1	6.2	8.1	6.7
7000	7.3	11.4	9.4	16.1	14.3	7.9	4.3	3.5	9.7	10.0	6.3	6.6	7.9	7.4	5.5
8000	10.3	13.3	11.2	15.6	15.2	8.2	3.9	2.5	11.0	9.6	6.5	8.8	7.0	5.7	5.5
9000	6.8	11.2	12.1	11.5	10.5	4.5	5.8	4.4	9.4	9.6	6.8	7.5	6.2	4.7	4.0
10000	4.3	6.0	5.7	3.9	4.2	3.0	4.3	5.9	5.6	4.6	3.5	1.9	1.5	1.9	2.7
11000	3.6	1.3	1.1	1.3	1.6	0.6	2.3	2.0	1.1	1.2	1.6	1.7	0.9	0.4	0.3
12000	0.8	0.4	0.5	0.5	0.1	1.5	1.7	1.5	0.5	0.2	0.6	0	0.2	0.4	0.3
13000	0.4	0.1	0.1	0.1	0.1	0.9	0.2	0.5	0	0.06	0.2	0	0	0.1	0
15000	0.1	0.1	0.2	0.1	0.2	0.3	0.2	0	0	0.04	0.1	0.3	0	0	0
Totals	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 6. Commercial Traffic Patterns at the Loadometer Stations

Subgrade Modulus	Best Choice of Pavement Thickness and corresponding Pavement Life based on 10,000 commercial axle loads per day per lane of traffic from the indicated Loadometer Stations														
	Heavy					Medium							Light		
	Sta. L-53	Sta. L-182	Sta. L-123	Sta. L-502	Sta. L-136	Sta. L-169	Sta. L-88	Sta. L-32	Sta. L-132	Sta. L-110	Sta. L-104	Sta. L-159	Sta. L-12	Sta. L-192	Sta. L-59
Very Good "k" over 275 psi/in	8 in. 16.8 yr.	8 in. 17.1	8 in. 17.2	8 in. 17.2	8 in 17.4	8 in 18.9	8 in 18.9	8 in 20.3	8 in 20.6	8 in 22.1	8 in 23.6	8 in 25.4	8 in 36.5	8 in 38.8	8 in. 42.6 yr.
Good "k" 225-275 psi/in	8 in. 11.3 yr.	8 in 11.4	8 in 11.4	8 in 11.5	8 in 11.6	8 in 12.3	8 in 12.6	8 in 12.2	8 in 13.9	8 in 14.6	8 in 15.8	8 in 16.6	8 in 24.7	8 in 26.1	8 in. 28.6 yr.
Fair "k" 175-225 psi/in	8 in. 4.9 yr.	8 in 4.9	8 in 5.0	8 in 5.1	8 in 5.1	8 in 5.2	8 in 5.5	8 in 5.0	8 in 6.1	8 in 6.4	8 in 6.9	8 in 7.1	8 in 11.0	8 in 11.6	8 in. 12.5 yr.
Poor "k" 100-175 psi/in	9 in. 3.0 yr.	8 in 3.1	9 in 3.1	8 in 3.1	8 in 3.2	9 in 3.3	9 in 3.7	9 in 3.6	8 in 3.7	8 in 4.0	8 or 9 4.1	9 in 4.5	8 in 6.8	8 in 7.1	8 in. 7.7 yr.
Very Poor "k" under 100 psi/in	9 in. 0.8 yr.	9 in 0.9	9 in 0.9	9 in 0.9	9 in 1.0	10 in 0.9	9 in 0.9	9 in 1.0	9 in 1.1	9 in 1.1	9 in 1.2	9 in 1.3	9 in 2.0	9 in 2.0	9 in. 2.2 yr.

Table 7. Pavement Thickness and Pavement Life for Various Traffic Patterns and Subgrade Support

Station	Average Daily Traffic (1951)	Percent Commer-cial	Average Axles Per Truck	Subgrade Modulus "k" (estimate)	Pavement Data			Remaining Pavement Life--Years		
					Thickness (inches)	Lane Width	Year of Original Construction	Field Estimate	By Design Method	Remarks
L-1	12,400	31	2.16	200	9-8-9	4 at 12'	1929	-1	-1 *	
L-2	2,200	29	2.20	250	9-7-9	2 at 9'	1924	1	3	
L-4	4,100	23	2.40	300	9-7-9	2 at 9'	1928	1	-2	
L-32	3,100	28	2.33	150	6-8-6	2 at 11'	1921	-14	-12	Resurfaced in 1938
L-53	3,800	19	2.34	250	9-7-9	2 at 10'	1936	5	5	
L-59	2,750	17	2.20	200	9-7-9	2 at 9'	1928	1	0	
L-88	3,200	18	2.20	200	6-8-6	2 at 11'	1922	-4	-5	Replaced in 1948
L-104	7,150	18	2.40	150	10-8-10	3 at 10'	1933	8	11	
L-110	7,700	28	2.65	200	9	4 at 12'	1944	8	9	
L-136	15,900	23	2.50	150	10-8-10	3 at 10'	1934	-3	-5	Resurfaced in 1949
L-192	8,500	17	2.12	200	9	2 at 10'	1935	8	8	
L-202	5,500	28	2.65	250	9-7-9	2 at 10'	1930	0	-2	
L-301	9,900	18	2.40	150	10-8-10	3 at 10'	1938	13	7	
L-302	13,200	18	2.40	250	10-8-10	2 at 17.5' 1 at 20'	1925	10	12	
L-461	8,000	20	2.65	200	10-8-10	3 at 10'	1930	8	11	
L-503	5,200	16	2.65	200	9	3 at 11'	1948	18	24	

* Survey and Study was made in 1952 and a reported life of -1 means pavement should have been replaced in 1951.

Table 8. Comparison of Remaining Pavement Life as Computed by Longitudinal Edge Loading Design Method and Reported by Field Inspection

from the edge of the pavement on such highways. Errors in this assumption are reflected only in Table 8 and do not affect the basic design method.

In order to ascertain whether or not the corner loading condition would have caused failure before the longitudinal edge loading, a parallel investigation was made of crack resistance factors with this loading. The only major difference in the method of attack was that the full commercial traffic count was considered to be effective for this loading. However, the lateral distribution of traffic on the lane and the reduction in stress at the critical section when a load was not within one-half foot of the corner, combined with the low unit stress values resulting from moderate loads (see Figure 2), materially reduced the total equivalent 5,000 pound wheel loads to only a fraction of those found for the longitudinal edge loading condition.

Traffic Pattern at Station	Pavement Thickness (inches)	Subgrade Modulus "k" (psi/in)	Lane Width (feet)	Pavement Life Based on 10,000 Commercial Axles per Lane per Day	
				Long. Edge Loading	Corner Loading
L-53	9	50	9	0.04 years	767 years
	8	200	9	0.27 years	104 years
	8	300	9	0.93 years	505 years
L-182	9	50	9	0.05 years	767 years
	8	100	9	0.17 years	48 years
L-123	9	50	9	0.05 years	383 years
	8	200	9	0.28 years	73 years
	8	200	12	5.0 years	1530 years
L-502	9	50	9	0.05 years	767 years
	8	100	9	0.17 years	48 years
L-136	9	50	9	0.06 years	383 years
	8	100	9	0.18 years	26 years
	8	100	12	3.2 years	536 years
L-169	10	50	9	0.05 years	Infinite
	9	100	9	0.18 years	Infinite
	8	200	9	0.29 years	38 years
L-88	9	50	9	0.05 years	383 years
	8	200	9	0.30 years	69 years

Note: 10,000 commercial axles per lane per day would be many times any normal loading. This number was used only for comparison purposes and for simplicity of calculations.

Table 9. Comparison of Pavement Life as Computed for Longitudinal Edge Loading and Corner Loading

A comparison of pavement life values based on 10,000 commercial axles per lane per day is given in Table 9. Since the 9-foot pavement lanes would reflect the most detrimental corner loading effects, most of the comparisons shown in Table 9 are for this slab width. No traffic lane would ever be subjected to as many as 10,000 commercial axles per day, but Table 9 clearly shows that the longitudinal edge loading is the critical loading position when lateral distribution of traffic and restrained warping stresses are considered. The pavement life values listed for the corner loading are, of course, absurd, and are listed only to illustrate the importance of the longitudinal edge loading. Occasionally, diagonal cracks will be found on pavement slabs, but these could be traced directly to loss of subgrade support beneath the corner of the slab. Of course with extremely heavy loads such as those of airplane wheels a pavement may crack across the corner from a single application of load. However, this paper presents a design method applicable only for loads of a magnitude that can be expected on highways.

CONCLUSIONS

1. Restrained warping stresses must be considered when Portland cement concrete pavement slabs are to be designed for highways.
2. For highway traffic the critical loading position of the wheel is along the longitudinal free edge of the pavement slab and not at the corner.
3. Highway pavement thicknesses should be chosen only after consideration is given to the number of repetitions of various wheel loads, and should not be chosen on the basis of a single application of a very heavy wheel load.
4. The semi-empirical design method illustrated in this paper can be easily and quickly applied by using the key "Percent Factors" of Table 4.
5. Table 7 clearly indicates that pavements need not be over 8 to 9 inches thick for the traffic encountered on highways today. This table may also be interpreted as showing that pavement life of thirty years may not be attained for some traffic conditions regardless of the condition of the subgrade.
6. Table 7 indicates that funds should be spent in improving the bearing capacity of the subgrade rather than being used for increased thicknesses of pavement.

SYMBOLS

σ_c = Maximum unit stress in the pavement slab due to a vertical load on the pavement at a distance a_1 from the corner. (psi)

σ_{ex} = Maximum longitudinal unit stress in the slab at a point six inches from the free longitudinal edge and at least five feet from the transverse edge due to a vertical load (P) at this point on the pavement slab. (psi)

S_{ex} = Maximum longitudinal unit stress six inches from the free longitudinal edge of the slab due to a temperature differential of Δt between the top and bottom of the pavement slab. (psi)

P = Vertical wheel load. (Pounds)

d = Thickness of pavement. (inches)

E = Modulus of Elasticity of concrete. (psi)

μ = Poisson's ratio.

k = Modulus of subgrade reaction. (psi/in)

ℓ = $\sqrt[4]{\dfrac{E\ d^3}{12(1-\mu^2)\,k}}$ = radius of relative stiffness. (inches)

a = Radius of circle of equivalent area of contact of wheel with pavement. (inches)

a_1 = $a\sqrt{2}$ = distance from slab corner along the bisector of corner angle to the center of the area over which the load is applied for the critical corner loading condition. (inches)

b = Radius of circle of equivalent distribution of pressure. (inches)

L = Maximum value of the radius of the circular area within which a redistribution of subgrade reactions is made. The center of the circle is at the point of load application. (inches)

Z = Ratio of reduction of the maximum deflection.

e = Coefficient of thermal expansion of concrete per degree Fahrenheit.

Δt = Temperature differential between the top and bottom of the pavement slab. (degrees Fahrenheit)

C = L_x/ℓ = a coefficient.

L_x = Length of pavement slab in longitudinal direction. (inches)